1975

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Discussion Paper 004

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Arthur J. Robson

RESEARCH PROGRAM: IMPACT OF THE PUBLIC SECTOR ON LOCAL ECONOMIES

Department of Economics
The University of Western Ontario
London Ontario Canada

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Department of Economics
University of Western Ontario
London, Ontario, Canada

Abstract

Theoretical models of urban structure which assume a radially-symmetric monocentric city imply that transportation pollution will cause cities to be too dispersed; whereas pollution from stationary sources might lead to cities which are too concentrated. This conflict is shown here not to arise in the real world where there are a multitude of destinations, with varying overall dispersion, for mobile pollution sources. Increased dispersion of the general structure of a city is shown to have the effect of lowering the level of pollution from transportation as well as from stationary sources. Increased provision of public transportation is shown to be effective in reducing the level of pollution related to transportation.

THE EFFECT OF URBAN STRUCTURE ON AMBIENT POLLUTION[1]

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1. Introduction

Theoretical models which I have developed focus on the effect of pollution in distorting the pattern of use of resources, particularly land, within an urban area. (See Robson, 1974.) Pollution produced by transportation will make cities too dispersed because individuals undervalue the cost of commuting and live too far from their destination--the CBD. On the other hand, pollution from stationary sources, even if it is fixed in amount, leads to cities which are too concentrated. This effect is due to the assumption that there are greater external costs of pollution for locations close to the centre of the city than there are for locations further away. There then appears to be a conflict between the policies to reduce pollution in the two cases. However, in the case of pollution from transportation, the assumption of a single central destination for all traffic is not innocent. For real cities greater dispersion of residences will be associated with greater dispersion of places of employment. Hence there is an offsetting effect to the increased output of pollution with increased dispersion--namely the greater dilution of the pollution. It is assumed that the level of pollution in the central city is the crux of the problem. Most of the data which exist are for stations in the central city, reflecting a similar judgment by the agencies monitoring pollution. In fact, increased dispersion of a city could lead to a decrease in the ambient level of pollution at all radial distances. (As in Robson, 1974.)

The questions which this empirical study addresses are the following:

(1) Can the significance of the effect that increased dispersion of a city will lead to a reduction in the ambient level at the centre be confirmed? This effect should exist for both pollution related to transportation and pollution from stationary sources, for a given quantity of emissions.

(2) How will increased dispersion affect the level of ambient pollution from transportation, for a given population of the city? The possibility is allowed here that increased dispersion will cause an increase in the per capita emission of transport pollution.

(3) How effective is the increased provision of public transportation in reducing the level of transport pollution? This can be investigated under either the hypothesis that the quantity of emissions be given or that the population be given.

(4) How does the degree of suburbanization of the city affect the level of pollution of either type of pollution at the centre of the city?

(5) How should meteorological influences be accounted for?

It will appear that the conflict between the prescriptions for reducing pollution of the two types does not exist in the real world.

2. The Model

The two pollutants considered are total suspended particulates, and nitrogen dioxide. Particulates are produced almost exclusively by stationary sources of various descriptions. Nitrogen dioxide is produced by transportation and by stationary sources in roughly equal amounts. Although carbon monoxide is more closely associated with transportation than is nitrogen dioxide, sufficient data do not exist for this pollutant. Predictions for the level of particulates and nitrogen dioxide are made using a meteorological model and data on the rate of emission for each pollutant in Section 4.2. These predicted levels are TSP* and NO* respectively. The relative level of nitrogen dioxide is predicted also on the assumption that the per capita rate of emission is constant. This predicted relative level is NO**. The actually observed average levels of particulates and nitrogen dioxide are TSP and NO respectively. The following are the dependent variables:

$$LHSTSP = TSP/TSP^* \quad (1)$$

$$LHS1NO = NO/NO^* \quad (2)$$

$$LHS2NO = NO/NO^{**} \quad (3)$$

This formulation has the advatange of reducing heteroskedasticity. These dependent variables are explained by parameters omitted from the meteorological model. The basic equations estimated are

$$LHSTSP = \alpha_0 + \alpha_1\ TEMP + \alpha_2\ POIN + \alpha_3\ GPOP \quad (4)$$

$$LHS1NO = \beta_0 + \beta_1\ TEMP + \beta_2\ POIN + \beta_3\ GPOP + \beta_4\ FPT70 \quad (5)$$

$$LHS2NO = \gamma_0 + \gamma_1\ TEMP + \gamma_2\ POIN + \gamma_3\ GPOP + \gamma_4\ FPT70 \quad (6)$$

All the independent variables are summarized, along with variables used in the meterological model, in Table II. Consider the predicted signs of each coefficient.

The variable TEMP is the mean annual temperature of the SMSA in 1970. It is expected that increased temperature would facilitate the diffusion of pollution and hence lower the ambient level. The coefficient of TEMP should be negative in (4), (5), and (6).

The variable POIN is the basic parameter of the dispersion of the city. For a given amount of emissions, as in (4) and (5), it is expected that increased dispersion will mean decreased ambient levels of pollution or that the coefficient of POIN be negative. For a given population in the case of transportation pollution, in (6), it is not clear a priori which sign the coefficient should have. If the effect of increased dispersion leading to more dilution overwhelms the effect of increased per capita emission, the coefficient will be negative. The construction of POIN is discussed in more detail in Section 4.1.

The variable GPOP is the ratio of the increase in population of the SMSA between 1920 and 1950 to the 1950 population. This is intended as a proxy for the degree of suburbanization, since the advent of the automobile made possible the large suburbs of cities which grew in this period. A faster rate of growth might then mean a greater concentration of stationary sources of pollution, for a given city size. In (4), then, the coefficient of GPOP would be positive. On the other hand, cities which grew in this period could allocate more land for roads than otherwise might be the case. It might then be that less pollution would be emitted by transportation. If this is the case the coefficients of GPOP in (5) and (6) would be negative.

The variable FPT70 is the fraction of the work-force which used public transportation to commute to work in 1970. For a given amount of emissions this would be an additional measure of the dispersion of automobile sources. Then the coefficient of FPT70 in (5) should be negative. For a given population, there will be the reinforcing effect of the decreased per capita production of pollution. Hence the coefficient of FPT70 in (6) should also be negative.

The results of estimating (4), (5), and (6) by ordinary least squares are presented in Table I. The percentage change in the level of pollution is calculated about the mean value of each dependent variable. The equations (5) and (6) were re-estimated without TEMP or GPOP, and the results are again in Table I. The usual F-statistics show that it is not possible to reject the null hypothesis that neither of these variables appear. The results are discussed in Section 3.

It should be noted that the value of R-squared is not appropriate for testing the complete specification of the model, since the constant has explanatory power here. However, the meteorological model is not the focus of attention.

3. Conclusions

(1) The mean annual temperature appeared to be a significant determinant of thelevel of particulates, but not of nitrogen dioxide. Higher temperatures mean less pollution as expected.

(2) The dispersion of a city is a significant determinant of the level of either pollutant, for a given quantity of emissions. The effect of increased dispersion is to lower the level of pollution. This is also true for transport pollution, nitrogen dioxide, when the population is given. This indicates that the increased dilution of pollution associated with

TABLE I

Summary of Results

Change in Independent Variable		Percentage of Change in Dependent Variables				
		TSP	1NO[a]		2NO[b]	
TEMP	+1.00	-6.25*	-1.83	-	2.69	-
POIN	+0.01[c]	-5.19**	-3.32**	-3.03**	-3.15**	-2.89**
GPOP	.0.01	2.89*	-0.09	-	-5.90**	-
FPT70	+0.01	-	-6.46**	-6.45**	-5.90**	-5.57**

* = significant at one-tailed 2.5% level
** = significant at one-tailed 0.5% level

[a]This is the predicted percentage change in the level of nitrogen dioxide, if the quantity of emissions is constant.

[b]This is the predicted percentage change in the level of nitrogen dioxide, if the population is constant.

[c]The meaning of an increase in POIN by 0.01 is illustrated by this example. Consider an SMSA with total area 1,000 square miles and population 500,000. An increase of POIN by 0.01 means that about 11,000 people shift from the central city to the suburbs. This increase in dispersion is accompanied by an increase in the dispersion of other economic activity, as in the sample.

increased dispersion outweighs the increase in the production of pollution per capita, for the cities in the sample.

(3) The rate of growth of an SMSA is a significant determinant of particulate pollution. Since this variable is a proxy for suburbanization, one would expect the positive sign found. It is either insignificant or a negative influence on the level of nitrogen dioxide which may reflect the effect of better roads in the more suburban cities.

(4) The provision of public transportation was a significant determinant of the level of nitrogen dioxide.

It seems city planning should promote the dispersion of the destinations, such as places of employment, of commuters in an urban area. This is a second-best solution, since the effect of people driving more than is optimal will persist. The results here are consistent with the hypothesis that the per capita production of pollution from transportation is almost constant. Increased dispersion will also help reduce the levels of pollution from stationary sources. An increase in the provision of public transportation would be effective in reducing the level of transportation pollution.

4. Data Appendices

4.1. Pollutants and Urban Structure Parameters

The data series for particulates and nitrogen dioxide are from unpublished tables from the Environmental Protection Agency, Cincinnati, Ohio (1974). Both observations of the ambient levels of pollution in the urban core and estimates of the total emission rates in the SMSA were used. The measurements of ambient pollution were annual averages--the geometric average for suspended particulates, TSP, but the arithmetic average for nitrogen dioxide, NO. The units were micrograms per cubic meter. The data for emission rates were estimated derived from two methods of different reliability. The "Rapid Survey Technique" was used for cities for which the results were available. This technique is an essentially complete inventory of quantities of pollution emitted. For the remainder of the cities, the EPA used published statistics to form less exact estimates of the rate of emission. This approach relied mainly upon figures available for fuel consumption in each SMSA. Allowance was made for control techniques when appropriate. The units were converted to micrograms per second to maintain consistency. The emission rate estimates were named TSPEM and NOEM for particulates and nitrogen dioxide respectively.

The pollution series were jointly available for a total of about 60 SMSA's. Some were eliminated due to gaps in other data, and also dropped were observations for SMSA's which are treated by the EPA as part of a larger "air-shed." This latter consideration meant dropping the SMSA's in the New York Standard Consolidated Metropolitan Area, those in the San Francisco Bay area,and those forming an "air-shed" from New Haven, Connecticut to Springfield, Massachusetts. Extremely low estimates for emission rates of one or the other pollutant were given for Montgomery, Alabama; Little Rock, Arkansas; and Utica, New York. These SMSA's were also omitted from the final sample, which consisted of 44 of the larger SMSA's with an essentially monocentric structure.

To measure the dispersion of an SMSA, the following index was used. Suppose that the population within an area which is geometrically a blow-up of the central city area from the centre of the SMSA, is proportional to a power of this area. Suppose that the SMSA area is such a blow-up of the central city area. Then, for constants K and n,

$$P(A) = K.A^n \tag{7}$$

where P(A) is the population residing within the area A. From the observations for the city and the SMSA, the value of n is

$$n = \frac{\log(HPC70/CP070)}{\log(MAREA/CAREA)} = POIN\ , \tag{8}$$

say, where MP070 and CP070 are the SMSA and city populations in 1970 respectively, and MAREA and CAREA are the SMSA and city areas in 1970 respectively. The higher the value of POIN, the greater the dispersion of the SMSA. If $n = 0$, the population is concentrated at the centre of the SMSA, if $POIN = 1$, the population is spread out uniformly.

4.2. Meteorological Model

The meteorological model used is due to Holzworth and Miller (1967). They predict the ground level concentration of pollution in the following situation. Consider a rectangular city of cross-wind width 2B meters and down-wind length L meters, where there is a wind with speed U meters per second, a uniform emission rate of Q micrograms per square meter per second, perfect reflection from the ground, and a "mixing height" of H meters. At the "mixing height" there is no tendency for lower air to rise further and this limits the mixing process. Holzworth and Miller assume that pollution is dispersed according to a Gaussian law where the dispersion parameters are empirically established functions of down-wind travel time for relatively vigorous mixing. They conclude that the most appropriate output of the model is the average concentration at ground level over the city. This is, assuming that B is large, $\overline{C}$, where

$$\overline{C}/Q = (3.994\ t_H^{1.115} + 4.453(T - t_H) + (T - t_H)^2/2H)/T \qquad (9)$$

where

$$t_H = 0.471\ H^{1.130} \qquad (10)$$

is the down-wind travel time until the presence of the mixing height begins to affect the ground level concentration, and

$$T = S/U \qquad (11)$$

is the down-wind travel time from the up-wind edge of the city to the down-wind edge. The expression (9) is valid if $t_H \leq T$, which is the case for all cities here. The dimension S is taken to be the square root of the SMSA area, MAREA.

The data on mixing height, H, and wind-speed, U, are obtained from Holzworth (1972). The geometric mean of the average morning and afternoon mixing heights for all days is used. The morning and afternoon observations correspond to the approximate minimum and maximum diurnal figures respectively. Wind-speed, U, is the average of the mean morning and afternoon observations. For a few SMSA's data for two stations in the network are interpolated. In all these cases, the data are close.

Stochastic variation in the level of pollution is neglected here. This aspect is important in considering the impact of pollution on people. However, it does not affect the present argument as to additional influences on pollution.

On the basis of the meteorological model, predictions as to ambient level of pollution can be made:

$$TSP^* = \frac{TSPEM}{MAREA} \cdot \frac{\overline{C}}{Q} \tag{12}$$

$$NO^* = \frac{NOEM}{MAREA} \cdot \frac{\overline{C}}{Q} \tag{13}$$

where TSP* and NO* are the predicted levels of particulates and nitrogen dioxide respectively, and $\overline{C}/Q$ is given by (9). Also, on the basis of a constant per capita rate of emission,

$$NO^{**} = \frac{MPO70}{MAREA} \cdot \frac{\overline{C}}{Q} \tag{14}$$

is a prediction of the relative level of pollution of nitrogen dioxide.

TABLE II

Summary of Variables Used

Variable	Description	Units	Source
TSP NO	Mean annual concentrations of particulates and nitrogen dioxide	Micrograms per cubic meter	Environmental Protection Agency (1974)
TSPEM NOEM	Estimates of the total rate of emission of the pollutants above	Micrograms per second	EPA
MPO70 CPO70	Metropolitan, city populations in 1970 respectively	Persons	City and County Data Book (1972)
MAREA CAREA	Metropolitan, city areas in 1970 respectively	Square meters	C & CDB
POIN	Index of dispersion of the SMSA population	None	Derived
FPT70	The fraction of the work-force using public transportation to commute to work in 1970	None	C & CDB
TEMP	The mean annual temperature in the SMSA in 1970	Degrees Fahrenheit	C & CDB
GPOP	The ratio of the increase in SMSA population between 1920 and 1950 to that in 1950	None	Bogue (1956)
$\overline{C}/Q$	The predicted ratio of average concentration to the uniform areal rate of emission	Seconds per meter	Holzworth (1970)
TSP* NO*	Predicted values of the levels of particulates and nitrogen dioxide	Micrograms per cubic meter	Derived
NO**	Predicted relative level of nitrogen dioxide based on constant per capita rate of emission	Persons-seconds per cubic meter	Derived
LHSTSP LHS1NO	TSP/TSP* and NO/NO* respectively	None	Derived
LHS2NO	NO/NO**	Micrograms per person per second	Derived

FOOTNOTES

[1]This paper is drawn from my Ph.D. thesis submitted to the Department of Economics, M.I.T., May 1974. I thank but do not implicate my committee, Professors R. M. Solow, M. L. Weitzman, and W. C. Wheaton.

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